COSMOS

COsmic-ray Soil Moisture Observing System

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A network of cosmic-ray probes distributed throughout the contiguous USA to provide soil moisture measurements at an intermediate spatial scale with arbitrary temporal resolution
Impact of soil moisture on precipitation
Spatial variations of soil moisture
(San Pedro River, AZ)

- Dry, before summer rains
- Wet, after 1 month of summer rains

Water content, weight %

Dry, before monsoon rains
Wet, after 1 month of summer rains
Cosmic-ray neutrons above the surface

Collision of cosmic-ray proton with atom

A collision between a high-energy cosmic ray particle and an atom in a photographic emulsion, as viewed through a microscope.

http://arc.iki.rssi.ru/mirrors/stern/Education/wcosray.html
Cosmic rays on Earth

- Primary - mostly protons and alphas
- Interact with magnetic field
  - intensity depends on geomagnetic latitude
- Interact with atmospheric nuclei
- Produce secondary particles - cascade
  - intensity depends on barometric pressure
- Produce fast neutrons
  - slowing down by elastic collisions
  - leads to thermalization
  - and then absorption

The last three processes depend on the chemical composition of the medium, in particular on its hydrogen content.

Space:
incoming high-energy cosmic-ray proton

Atmosphere:
generation of secondary cosmic rays

Ground:
slowing down thermalization and absorption
Moderating (slowing down) power

\[ \phi (E) = \frac{Q}{E \Sigma (N \cdot \sigma_{sc} \cdot \xi) } \]

- \( \phi (E) \) - flux of neutrons of energy \( E \)
- \( Q \) - strength of source function
- \( N \) - number of atoms of an element
- \( \sigma_{sc} \) - scattering cross section for an element
- \( \xi \) - log decrement of energy per collision
- \( \sigma_{sc} \cdot \xi \) - slowing down power for an element
- \( \Sigma (N \cdot \sigma_{sc} \cdot \xi) \) - slowing-down power of the medium
Top ten elements (bold letters) contributing to macroscopic scattering and absorption cross sections in an "average rock."

<table>
<thead>
<tr>
<th>Element</th>
<th>(A)</th>
<th>(\sigma_{sc})</th>
<th>(\sigma_{th})</th>
<th>NC</th>
<th>(\xi)</th>
<th>SP</th>
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<tbody>
<tr>
<td>H</td>
<td>1.0079</td>
<td>22.02</td>
<td>0.3326</td>
<td>18</td>
<td>1.00</td>
<td>22.016</td>
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<td>B</td>
<td>10.811</td>
<td>5.24</td>
<td>767</td>
<td>103</td>
<td>0.174</td>
<td>0.912</td>
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<td>C</td>
<td>12.011</td>
<td>5.551</td>
<td>0.0035</td>
<td>113</td>
<td>0.158</td>
<td>0.875</td>
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<td>O</td>
<td>15.9994</td>
<td>4.232</td>
<td>0.00019</td>
<td>149</td>
<td>0.120</td>
<td>0.508</td>
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<td>Na</td>
<td>22.9898</td>
<td>3.28</td>
<td>0.53</td>
<td>211</td>
<td>0.085</td>
<td>0.277</td>
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<td>Mg</td>
<td>24.305</td>
<td>3.71</td>
<td>0.063</td>
<td>223</td>
<td>0.080</td>
<td>0.297</td>
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<td>Al</td>
<td>26.9815</td>
<td>1.503</td>
<td>0.231</td>
<td>247</td>
<td>0.072</td>
<td>0.109</td>
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<tr>
<td>Si</td>
<td>28.0855</td>
<td>2.167</td>
<td>0.171</td>
<td>257</td>
<td>0.070</td>
<td>0.151</td>
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<td>Cl</td>
<td>35.4527</td>
<td>16.8</td>
<td>33.5</td>
<td>323</td>
<td>0.055</td>
<td>0.930</td>
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<td>K</td>
<td>39.0983</td>
<td>1.96</td>
<td>2.1</td>
<td>355</td>
<td>0.050</td>
<td>0.099</td>
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<td>Ca</td>
<td>40.078</td>
<td>2.83</td>
<td>0.43</td>
<td>364</td>
<td>0.049</td>
<td>0.139</td>
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<td>Ti</td>
<td>47.88</td>
<td>4.06</td>
<td>6.43</td>
<td>434</td>
<td>0.041</td>
<td>0.167</td>
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<td>Mn</td>
<td>54.9381</td>
<td>2.17</td>
<td>13.3</td>
<td>497</td>
<td>0.036</td>
<td>0.078</td>
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<td>Fe</td>
<td>55.847</td>
<td>11.62</td>
<td>2.56</td>
<td>505</td>
<td>0.035</td>
<td>0.411</td>
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<td>Cd</td>
<td>112.411</td>
<td>6.5</td>
<td>2520</td>
<td>1009</td>
<td>0.018</td>
<td>0.115</td>
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<td>Sm</td>
<td>150.36</td>
<td>39</td>
<td>5922</td>
<td>1348</td>
<td>0.013</td>
<td>0.516</td>
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<td>Gd</td>
<td>157.25</td>
<td>180</td>
<td>49700</td>
<td>1409</td>
<td>0.013</td>
<td>2.280</td>
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</table>

\(A\) - atomic mass (g/mole); \(\sigma_{sc}\) - elastic scattering cross-section (barns; 1 barn = \(10^{-24}\) cm\(^2\)); \(\sigma_{th}\) - thermal neutron capture (absorption) cross-section; NC - number of collisions to thermalize a 1-2 MeV neutron; \(\xi\) - average log decrement of energy per neutron collision; SP - stopping power (roughly equal to \(\xi\sigma_{sc}\)).
Neutron response to soil moisture

Volumetric soil moisture content

Neutron flux (relative)

Thermal

Fast (and epithermal)

-granite
-basalt
-quartz
-limestone
Calibration function

![Graph showing Calibration function with data points and a least squares fit to MCNPX. The x-axis represents Relative neutron flux, and the y-axis represents Volumetric water content.]
Measurement volume

- 86% of neutrons within radius of 350 m
- Radius increases with decreasing pressure
- 86% of neutrons within depth of 60 cm
- Depth decreases to 12 cm in wet soils
Variations of cosmic-ray intensity

In space:

- with latitude and longitude (geomagnetic cutoff rigidity)
- with altitude (pressure)
- with depth (mass) - not important for this application

In time:

- due to pole position changes
- due to solar activity
- due to barometric pressure changes
- due to paleomagnetic intensity changes - not important
- due to long-term galactic cosmic-ray flux changes - not important
Vertical cutoff rigidity for Epoch 1980
Variations with altitude (pressure)

Zugspitze:
47.4 °N (3.3 GV)
2962 m (740 g/cm²)

Munich:
48.2 °N (3.1 GV)
500 m (980 g/cm²)

Hamburg:
53.5 °N (2.0 GV)
0 m (1033 g/cm²)
Temporal variations of neutron intensity

Long-term variations (55 years, five solar cycles): ca. 30%
Cosmic-ray probe

\[ 3\text{He}(n,p)\text{H}+p \quad Q=0.2 \text{ MeV} \]

\[ \text{thermal neutron detector} \]

\[ \text{fast neutron detector} \]

\[ \text{HDPE moderator} \]

\[ \text{high voltage} \]

\[ \text{temperature, humidity and barometric pressure sensors} \]

\[ \text{data logger} \]

\[ 3\text{He} \quad @ \text{2.7 atm} \]
Cosmic-ray probe
Precision of COSMOS probe

Soil moisture, wt. %

Soil moisture uncertainty, wt. %

Soil moisture, wt. %
Precision of COSMOS probe
Hours necessary for 2% measurement
Field application
San Pedro River, AZ

- Derived soil moisture from cosmic-ray neutron data
- Compared with gravimetric samples
- With TDR results
- And with precipitation amounts
The cosmic-ray soil moisture probe

Sensitive to soil moisture content
Insensitive to soil chemistry
Non-invasive, no contact measurement
Probe above the ground measures neutrons emitted from soil
No artificial source of radiation
Fully automatic measurement and data transfer
Configurable remotely
Integrated soil moisture over a footprint of ~700 m
Integrated soil moisture over a depth of 12-70 cm
The COSMOS network

(1) 500 stations distributed across the contiguous USA

(2) Each station has a cosmic-ray probe that provides near real-time soil moisture data averaged over a footprint of ~700 m

(3) data can be integrated and reported with arbitrary temporal resolution (the default time is 1 hour)

(3) Each station has temperature, pressure and relative humidity sensors

(4) Intended uses:

(a) soil moisture initialization in weather and short-term climate forecasting;

(b) land-atmosphere energy and mass exchange;

(c) drought monitoring;

(d) ecohydrology;

(e) ground validation of satellite remote sensing methods.